RF Project 1444

THE OHIO STATE UNIVERSITY

RESEARCH FOUNDATION

1314 KINNEAR ROAD COLUMBUS 12, OHIO

THE USE OF PHOTOGRAMMETRIC METHODS TO INVESTIGATE SURFACE MOVEMENT OF THE ANTARCTIC ICE SHEET

(Preliminary Report)

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Preliminary Report

by

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Columbus 12, Ohio

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On: THE USE OF PHOTOGRAMMETRIC METHODS TO INVESTIGATE SURFACE MOVEMENT OF THE ANTARCTIC ICE SHEET

For the period: 1 July 1962 - 31 May 1963

Prepared by: Robert B. Forrest
Principal Investigator

Date: August 1963

FOREWORD

This preliminary report was prepared by Mr. Robert B. Forrest, Research Associate, Department of Geodetic Science, The Ohio State University, and Principal Investigator under National Science Foundation Grant G-23006, OSURF Project No. 1444, with Dr. Arthur J. Brandenberger, Department of Geodetic Science, The Ohio State University, as Project Supervisor, and Dr. Colin B. B. Bull, Institute of Polar Studies, The Ohio State University, as Assistant Supervisor.

OSURF Project No. 1444 covers research performed by Dr. A. J. Brandenberger, Supervisor; Dr. C. B. B. Bull, Assistant Supervisor; Mr. R. B. Forrest, Miss M. W. Hindman, and Mr. R. M. Koerner, Research Associates; Mr. D. T. Dickson, Research Assistant; Mr. Simha Weissman and Miss V. K. Verner, Technical Assistants,

In addition, the author wishes to acknowledge the assistance of Dr. Arthur Mirsky, Mr. R. K. H. Adler, Mr. Graeme Johnstone, Mr. Larry Martin, Mr. Robert Mason, Mr. Herbert Mehrling, and Mr. John Molholm in the preparation and accomplishment of the field work; and Mrs Vera N. Hoff as Secretary.

ABSTRACT

A study is being made to measure the surface movement of a part of the Antarctic ice sheet, using aerial strip triangulation with independent geodetic control. After placing 134 photographic markers between Byrd Station and Mt. Chapman, a distance of 365 km, an overlapping strip of aerial photographs was taken. Using Mt. Chapman as the only fixed reference, together with a very limited amount of field work, the positions of the markers will be determined by aerial triangulation. After a certain time interval of one or two years another strip of photographs will provide changed marker positions. This preliminary report explains the method of aerial triangulation and discusses the initial field work performed during the 1962-1963 austral summer.

TABLE OF CONTENTS

TABLE OF CONTENTS
continued

LIST OF ILLUSTRATIONS

LIST OF TABLES

THE USE OF PHOTOGRAMMETRIC METHODS
TO INVESTIGATE
SURFACE MOVEMENT OF THE ANTARCTIC ICE SHEET
(PRELIMINARY REPORT)

I. INTRODUCTION

A. PURPOSE

This research is an attempt to use photogrammetric methods to measure the surface movement of portions of the Antarctic ice sheet. With these methods, the surface velocity can be evaluated in areas hundreds of kilometers from the nearest fixed point.

A detailed knowledge of the surface velocity of the ice over wide areas is required in direct assessments of the mass balance of the ice sheet. From the same information, values of the surface horizontal strain rates can be obtained. These values are required in interpreting the deformation of deep holes drilled into the ice sheet, and in estimating the stress history and age of the ice recovered from the lower layers of the ice sheet.

B. THE USE OF PHOTOGRAMMETRY FOR ICE MOVEMENT STUDY

Traditional measuring methods require extensive field work to determine ice surface movement over a large area. Such methods extend the measuring process of the moving surface over several months. An alternate method is now provided by aerial strip triangulation with independent geodetic control. This method makes use of strips of aerial photographs, which give a fast record of the area under study.

A strip of vertical aerial photography is taken with approximately sixty percent overlap between consecutive photographs. The photographs then are connected, in effect, to form a continuous model of the photographed surface. This process is called aerial triangulation. When this strip model is adjusted and fixed in scale and position, it forms a true spatial model of the portion of the surface of the earth that was photographed. In this case, the surface is that of a slowly moving ice sheet.

Two fixed points at one end of the strip establish the origin and direction of a plane coordinate system. Photographic markers fixed on the ice surface can be assigned values in this coordinate system by the aerial triangulation. Later aerial photography of the same markers will, when triangulated and referred to the same fixed location, yield new coordinate values in the same system. Thus, displacement vectors can be determined for all marked points in the strip.

If the photography is repeated for several consecutive summer seasons, variations in the annual surface movement may be determined.

C. SCOPE OF THIS REPORT

This preliminary report is limited to a description of the photogrammetric equipment and methods used, and to discussion of the initial field work performed during the 1962-1963 austral summer. A later report will cover the aerial triangulation procedure, and will give the February, 1963 coordinate values for the photographic markers that were established during the field work.

D. LOCATION OF THE AREA

A line of photographic markers was erected from New Byrd Station ($80^{\circ}01'$S, $119^{\circ}31'$W) southeast to Mt. Chapman ($82^{\circ}34'$S, $105^{\circ}55'$W), a distance of 365 km (Fig. 1). Mt. Chapman, one of the Whitmore Mountains, is the nearest known fixed point to Byrd Station.

Along the marker route, the surface elevation, 1,530 m above sea level at Byrd Station, remains nearly constant for 130 km, and then rises to 2,060 m at Mt. Chapman. The mountain rises about 700 m above the snow surface.

No crevasses were encountered along the marker route, although a few crevasses are present less than two kilometers from Mt. Chapman. Since the final surveying work was performed more then four kilometers from the mountain, these crevasses were no danger.

Mt. Chapman presents a granite face five kilometers long as it is approached from the northwest. Viewed from this direction, the highest peak is near the center, with a lower peak at the left. A lower ridge of more heavily weathered rock extends to the right.

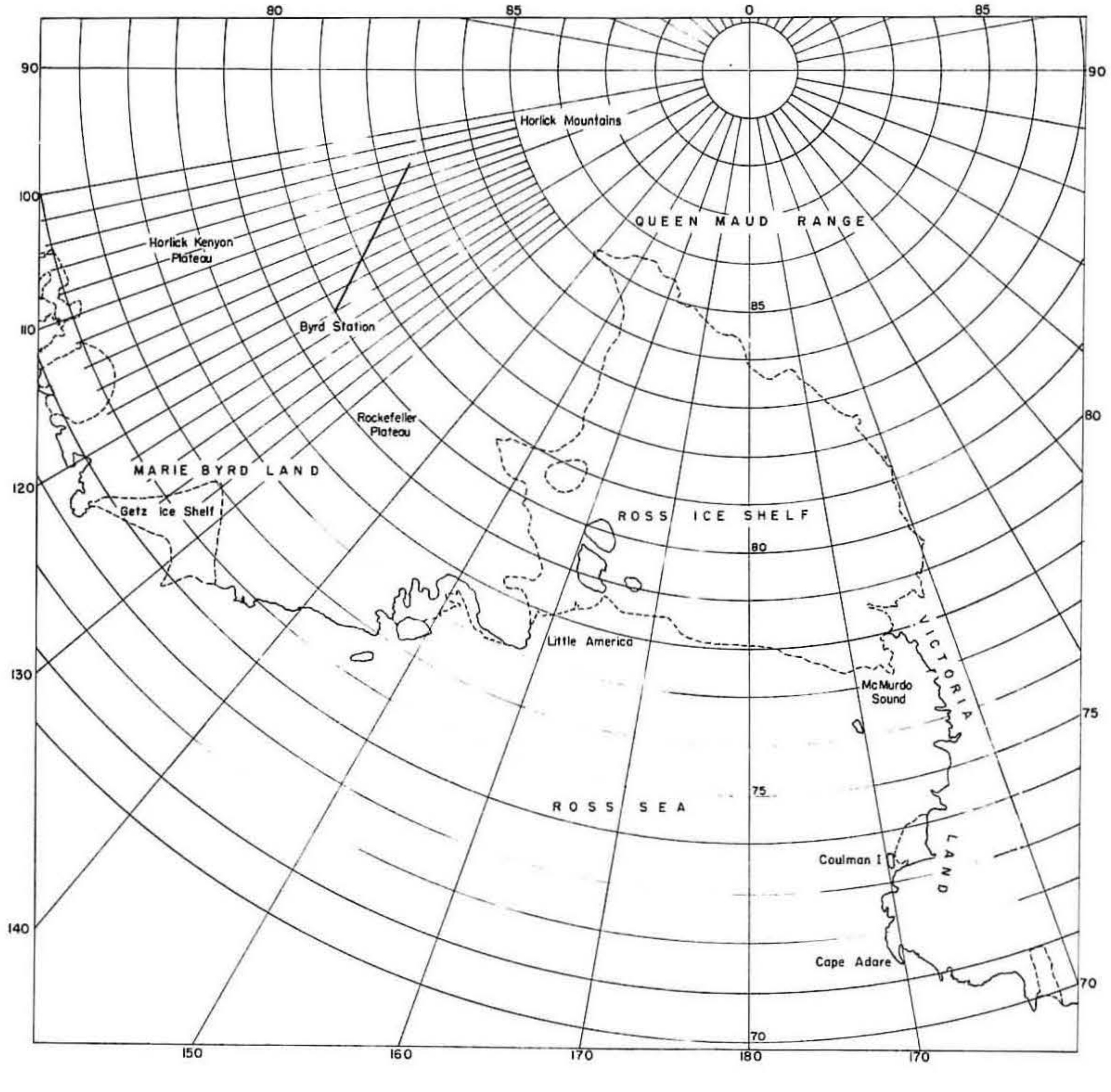


Figure 1. Location of the Area Being Studied

II. THEORY OF THE PHOTOGRAMMETRIC METHOD

A. AERIAL TRIANGULATION WITH INDEPENDENT GEODETIC CONTROL

A strip of vertical aerial photographs with sixty percent overlap is taken of the area in question. The first two photographs are placed in a first-order stereo instrument. In the instrument the photographs form an optical model of the overlap area. This model can be viewed and measured stereoscopically. It can be oriented to the same area on the earth's surface if the following control information is present:

1) the elevations at three or more identifiable non-colinear points (for spatial orientation), and

2) the ground distance between two identifiable points whose ground coordinates are known (for scale and horizontal orientation).

These necessary ground control points effectively fix the first two photographs in space. The photographs are fixed relative to the vertical datum of the elevations and the direction of the known distance. Thus, a plane coordinate system can be established in the model, with any desired origin and orientation. The same system can be re-established in any other pair of photographs of the same area, as long as the control information remains fixed and photographically identifiable.

A second model is formed by stereoscopically orienting the third photograph to the second, with the second photograph still fixed by the original orientation. This fixes the third photograph in space. The triangulation continues in this manner to the end of the strip. Each photograph has then been fixed to the preceding photograph, and all of the optical models lie in a common coordinate system. Thus, rectangular coordinates x,y,H in the same coordinate system can be obtained for points throughout the strip.

If the triangulation procedure is errorless, the last model will have the correct scale, azimuth, and slope relative to the first model (after considering earth curvature). However, errors are always introduced by many factors, including small errors in connecting the photographs, mechanical and optical errors in the stereo instrument, insufficiently compensated camera objective distortion, and poor dimensional stability of the film.

Since errors are present in the triangulation, the x,y,H values obtained in the triangulation must be adjusted. Both irregular and systematic errors occur in aerial triangulation. Summation of the irregular and systematic errors produces regular error curves of second or third degree for such strip triangulations. In the strip coordinate system, the corrections Δx and Δy for a point with strip coordinates x,y can be expressed in the forms:

$$\Delta x = a_o + a_1 x + a_2 x^2 + c_1 y + 2c_2 xy \quad + (a_3 x^3 + 3c_3 x^2 y), \text{ and} \qquad (1a)$$

$$\Delta y = c_o - c_1 x - c_2 x^2 + a_1 y + 2a_2 xy \quad + (-c_3 x^3 + 3a_3 x^2 y), \qquad (1b)$$

where the coefficients a and c must be determined (Ghosh, 1962, and others). The terms in parentheses need not be considered for distances of less than approximately 50 km or 20 models.

Heights are read as their true ground values in meters or feet in the stereo instrument. True slopes are used in the adjustment of the triangulation. Therefore, a height correction, ΔH, for a point with strip coordinates x,y will be referred to ground distances. The height correction can be expressed by an equation of the form

$$\Delta H = d_o + d_1 \bar{X} + d_2 \bar{X}^2 + i_o \overline{XY} \qquad + (d_3 \bar{X}^3 + i_2 \bar{X}^2 \bar{Y}) \qquad (1c)$$

where

$$\bar{X} = \frac{x}{\text{strip triangulation scale}} \, ,$$

$$\bar{Y} = \frac{y}{\text{strip triangulation scale}} \, ,$$

and the coefficients d and i must be determined.

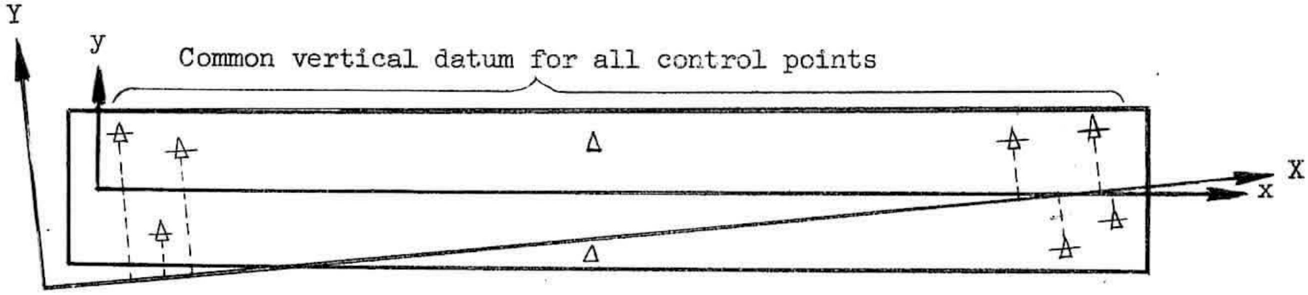
Ground control in the first model is not sufficient to solve the correction equations. Additional ground control points having large values of x are required, hence, these points are located at or near the other end as well as in the middle of the strip, when second-degree adjustment equations are used. When third-degree equations are required, an additional control area is added.

In conventional aerial triangulation, all planimetric control points are referred to the same ground coordinate system, and all heights are referred to a common vertical datum (Fig. 2). Using this information the coordinate corrections can be found by:

1) transforming the ground X,Y system into the strip x,y system,

2) finding the x,y,H corrections Δx, Δy, ΔH, for the control points, by the differences between transformed ground coordinates and strip coordinates, and

3) using the known corrections and coordinate values, solving equations (1) for the correction coefficients a, c, d, and i.



△ Ground Control Points

Figure 2. Conventional Ground Control for Aerial Strip Triangulation

Thus, unless existing geodetic control is available, the areas of control points must be connected by conventional surveying traverse, triangulation, trilateration, and leveling methods, to refer all the points to the same system. Such field work is tedious, especially under Antarctic conditions, and fortunately can be avoided by using the method of <u>aerial strip triangulation with independent geodetic control</u> (Karara, 1956, 1957).

In this method, control information in a control area is limited (Fig. 3) to only:

1) a known ground distance at both ends of the strip
2) the relative heights at three or more non-colinear photo-identifiable points at both ends of the strip, and
3) the azimuth of the ground distance, at each end of the strip. Note that <u>no</u> ground coordinate system is required.

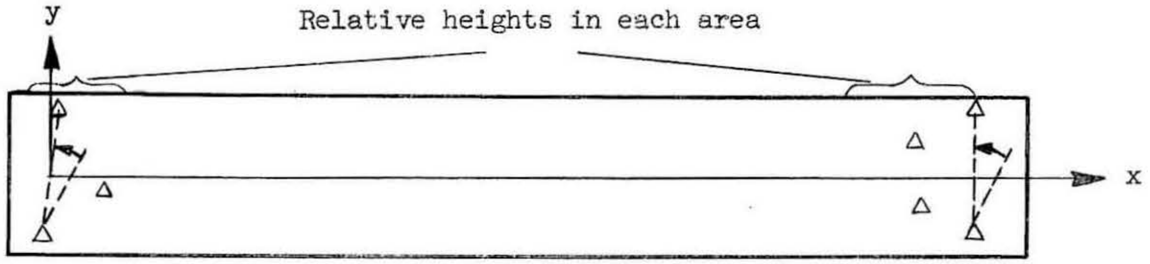


Figure 3. Ground Control for Aerial Strip Triangulation With Independent Geodetic Control

The azimuth may be a true geographic azimuth converted to the strip system. It may also be a fictitious azimuth (especially in high latitudes), provided that all other control azimuths have the same reference.

If absolute height values are required, at least one vertical control point must have an absolute elevation.

In equations (1) only second degree terms are required for <u>strips of less than 50 km or 20 models</u>. Thus, ground control is necessary only at the ends of the strip. When y is constant, the planimetric correction equations have the forms (Brandenberger, 1951):

$$\Delta x = A_o + A_1 x + A_2 x^2 \tag{2a}$$

$$\Delta y = C_o + C_1 x + C_2 x^2 \tag{2b}$$

The constants A_o and C_o can be made zero by a judicious choice of the strip coordinate system origin.

If we differentiate (2) with respect to x, we have

$$\frac{d\Delta x}{dx} = A_1 + 2A_2 x = \delta_s \text{ , the scale correction, and} \tag{3a}$$

$$\frac{d\Delta y}{dx} = C_1 + 2C_2 x = \delta_\alpha \text{ , the azimuth correction.} \tag{3b}$$

In the first model, at x equals zero, the scale and azimuth corrections are known from the given independent geodetic control information and the triangulated strip coordinates. Thus, the coefficients A_1 and C_1 are simply equal to the scale and azimuth corrections, respectively, in the first model. The values of A_2 and C_2 are found from the information known at the end of the strip, using the x coordinates at the end and the known A_1 and C_1 values.

Also, the y coordinates must be corrected for scale error and the x coordinates for azimuth error. The correction equations have the forms

$$\Delta y_s = G_o y + G_1 xy \text{ , and} \tag{4a}$$

$$\Delta x_\alpha = E_o y + E_1 xy \text{ .} \tag{4b}$$

Differentiating (4) with respect to y gives

$$\frac{d\Delta y_s}{dy} = G_o + G_1 x = \delta_s \quad , \quad \text{and} \tag{5a}$$

$$\frac{d\Delta x_\alpha}{dy} = E_o + E_1 x = \delta_\alpha \quad . \tag{5b}$$

At x equals zero,

$$G_o = A_1 = \delta_{s_o} = \text{scale correction in the first model, and} \tag{6a}$$

$$E_o = C_1 = \delta_{\alpha_o} = \text{azimuth correction in the first model} \tag{6b}$$

Therefore,

$$C_1 = 2A_2 \quad , \quad \text{and} \tag{7a}$$

$$E_1 = 2C_2 \quad . \tag{7b}$$

Combining the corrections to x and y for scale and azimuth errors, the complete correction equations are

$$\Delta x = A_1 x + A_2 x^2 + C_1 y + 2C_2 xy \quad , \quad \text{and} \tag{8a}$$

$$\Delta y = C_1 x - C_2 x^2 + A_1 y + 2A_2 xy \quad . \tag{8b}$$

The negative sign in (8b)is necessary because a positive azimuth correction produces a negative y correction. The four coefficients thus are determined by two sets of scale and azimuth corrections, one set at x equals zero and the other at or near the other end of the strip.

Return to (1c), the height correction equation. The relative heights determined by the aerial triangulation are not the same as the true relative heights, due to the earth curvature and aerial triangulation errors. The effect of earth curvature can be included in equation (1c). Again, for short distances it is permissible to use only the second-degree correction equation.

In the field work, the heights of the elevation control points are determined relative to each other. The approximate surface distance between the elevation control points is known from their x,y strip coordinates and the triangulation scale. From the relative heights and approximate surface distances, true angles of slope can be found. From the x,y coordinates of the points, these slopes can be resolved into slopes in the x and y directions. Thus, the necessary slope corrections in the x and y directions are known for the triangulation strip model, in the areas of vertical control points. The longitudinal slope correction, or slope about the y axis, is $\delta\varphi$, and the lateral slope correction about the x axis is $\delta\omega$.

If y is constant, and if $\overline{X}$ is less than 50 km or 20 models, the the height correction, ΔH, of a point with coordinates $\overline{X},\overline{Y}$ as defined earlier, can be expressed as

$$\Delta H = D_o + D_1\overline{X} + D_2\overline{X}^2 \quad . \tag{9}$$

Differentiation of (9) with respect to $\overline{X}$ gives

$$\frac{d\Delta H}{d\overline{X}} = D_1 + 2D_2\overline{X} = \delta\varphi \quad . \tag{10}$$

In the first model, D_1 is equal to the known longitudinal slope correction in this model, where x (and therefore $\overline{X}$)is equal to zero. Then in the last model, D_2 can be found, knowing x and the longitudinal tilt correction at the end of the strip.

Lateral tilt causes an error which can be corrected by

$$\Delta H_t = I_o\overline{Y} + I_1\overline{XY} \quad . \tag{11}$$

Differentiating (11) with respect to $\overline{Y}$, the lateral tilt correction is

$$\frac{d\Delta H_t}{d\overline{Y}} = I_o + I_1\overline{X} = \delta\omega \tag{12}$$

From the two known values of $\delta\omega$, I_o and I_1 may be determined in the same way as D_1 and D_2..

Combining the terms, the final correction equation is

$$\Delta H = D_o + D_1\overline{X} + D_2\overline{X}^2 + I_o\overline{Y} + I_1\overline{XY} \quad . \tag{13}$$

Here D_o is known if at least one absolute elevation is available. If an absolute elevation is present in the first model, the instrument height counter is set to the correct value at the time of absolute orientation of the first model. In this case, D_o equals zero.

For strips longer than 50 km or 20 models, third-degree error equations and three areas of independent geodetic control are used. One area is located at each end of the strip and the third area is near the center. Derivations similar to those given above may easily be performed for this case (Forrest, 1960; Ghosh, 1962).

In extremely long triangulations, many areas of geodetic control can be used; for example, in this research, seven are used. In this case, the adjustments can be applied to overlapping sections of the strip, using three consecutive control areas for the adjustment of each section (Fig. 4).

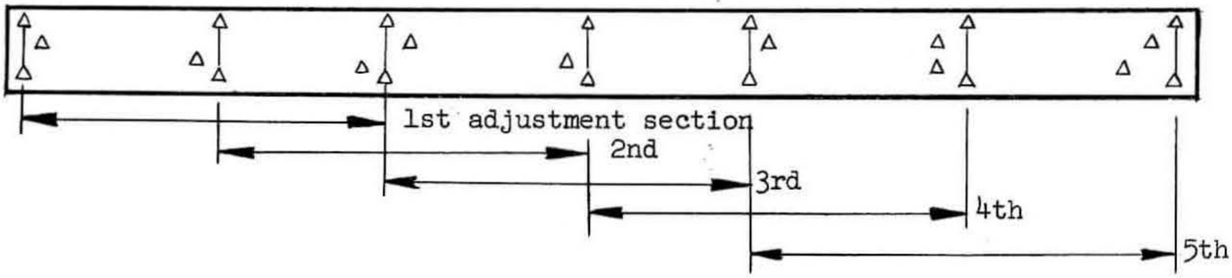


Figure 4. Adjustment by Sections for a Long Strip

Other combinations of three control areas are also possible, such as two terminal areas and one interior area. Thus, many adjusted sets of coordinates for each point can be obtained. The differences will provide a good indication of the accuracy ~~and~~ of the method.

B. ADDITIONAL CONTROL INFORMATION

Due to the design of the marker pattern in each control area, each geodetic control area will provide two or three base lines and azimuths instead of one. Two and sometimes three values of x- and y- slope can be determined in each area. This extra data will permit a valuable check on the adjustment parameters in each area.

In the initial triangulation to be performed in this study, some additional control will be available. At each marker location between control areas, the horizontal angle was measured between the succeeding and preceding markers (Fig. 5 and Table 1). During the aerial triangulation, these angles may be used to control the azimuth of the strip to an accuracy previously unattainable in aerial triangulation.

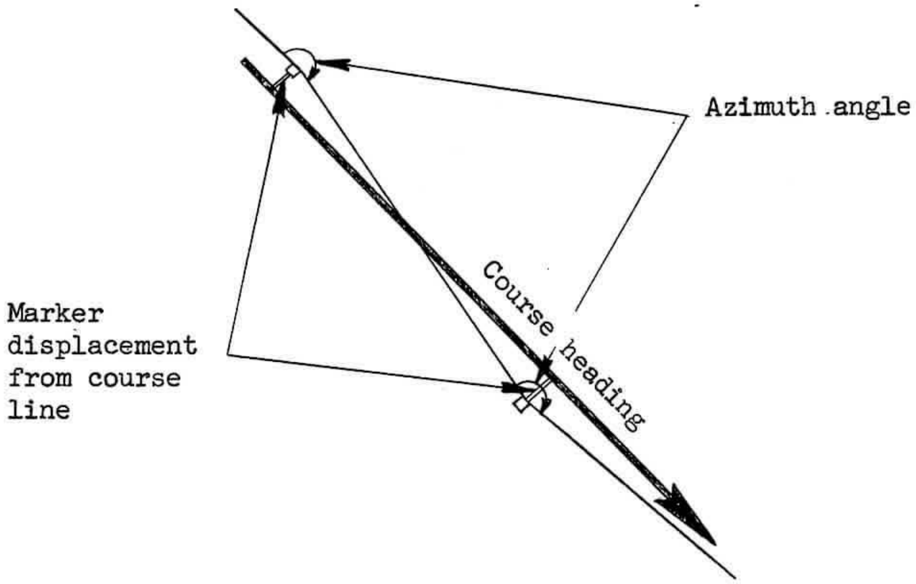


Figure 5. Azimuth Angle and Marker Displacement between Arrays

III. FIELD WORK

A. GENERAL

The field party participants were Mr. Robert B. Forrest, Research Associate and Principal Investigator (Surveyor), Mr. Roy M. Koerner, Research Associate and Glaciologist, Mr. Donald T. Dickson, Research Assistant, and Mr. Graeme Johnston, Mechanic and Field Leader. Dr. Colin B. B. Bull, Assistant Supervisor, was with the field party for one week, making gravimetric measurements at several points near Mt. Chapman. Dr. A. J. Brandenberger, Project Supervisor, spent several weeks at Byrd Station, McMurdo, and the South Pole to assist in the preparation of the field traverse party and to perform texture studies. The field party left Byrd Station on December 16, 1962, and returned January 30, 1963.

From Byrd Station, the photographic markers were placed about four kilometers apart on a course toward Mt. Chapman. The straightest possible line was followed until Mt. Chapman was sighted from a distance of ninety kilometers. When sighted, the mountain peak lay approximately forty minutes of arc to the left of the course. The course was changed to bring the last markers more directly into line with the peak. This was done gradually to avoid a dog-leg in the marker line.

Seven control arrays were surveyed, positioned along the marker line as shown in Fig. 6. The strip thus was divided into six approximately equal parts. The required number of arrays in the strip was determined in the following manner:

1) Measurement of the horizontal positions of the array markers in the triangulation is to be performed within a standard error of plus or minus one meter.
2) In the photograph, considering the inferior camera objective used, array measurement accuracy is estimated at $\pm$ 0.02 mm standard error. (With a precision camera this would be $\pm$ 0.01 mm.)
3) Therefore, the scale of the photography must be 1/50,000 or larger. A scale of 1/40,000 was selected to provide a 20 per cent accuracy safety factor. This was necessary because of the many unknown parameters in the project.
4) The camera focal length of approximately 150 mm dictates a flying height of 6,000 m above terrain to satisfy the scale requirement.

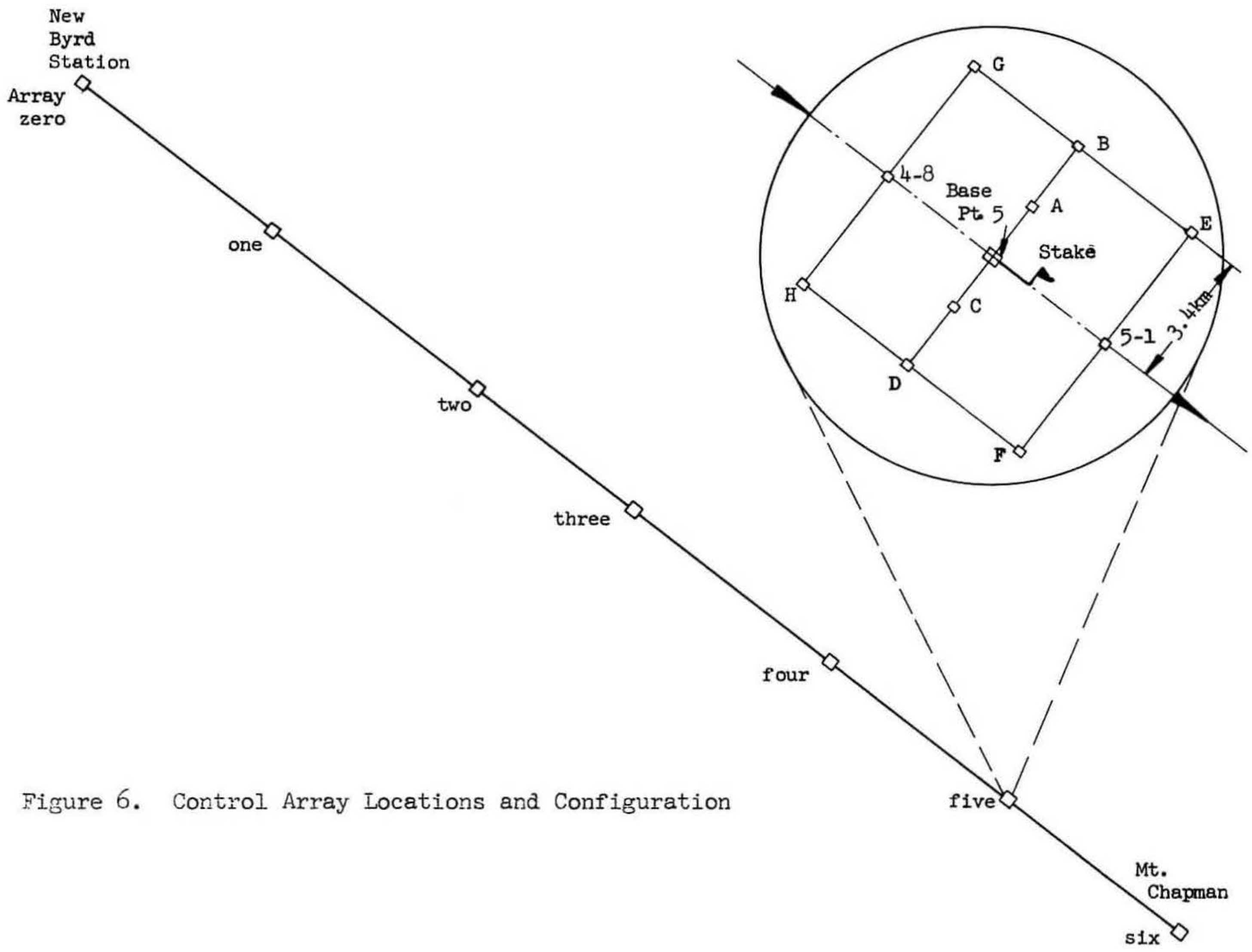


Figure 6. Control Array Locations and Configuration

5) The negative size of 23 by 23 cm, together with the 60 percent overlap requirement, determines that about 100 photographs are required for the distance of about 370 km, or a photographic air base of 3.7 km.

6) The aerial triangulation errors are a function of the number of models between control arrays. A division of the strip into 5 parts (6 control arrays) means approximately 20 models between arrays.

This is considered as being feasible under normal conditions. Actually the Byrd Station-Whitmore Mountain strip was divided into 6 parts (16 and 17 models per section) to provide an additional safety factor, again necessitated by the unknown parameters in the work.

B. MATERIAL

1. Markers

The design of the photographic markers developed from discussions among Dr. Richard P. Goldthwait, Director, Dr. Arthur J. Mirsky, Assistant Director, Dr. Arthur J. Brandenberger, Research Supervisor, Dr. Colin B. B. Bull, Assistant Supervisor, and Mr. Herbert Mehrling, all of the Institute of Polar Studies, The Ohio State University. Mr. George Toney of the Office of Antarctic Programs, National Science Foundation, suggested certain modifications.

The markers are to appear on the photographs as approximately 0.04 mm in diameter. This is the size of the measuring mark in the stereo instrument (Wild Autograph A7). A marker board 1.6 m square thus is the correct size for the 1/40,000 scale photography. This was finally rounded off to boards 1.52 m (5 feet) square, mounted horizontally on 10 foot long aluminum conduits, 3 inches in diameter.

Wind tunnel tests at several velocities up to 125 mph were carried out on model markers. Dr. B. E. Gatewood and Mr. R. G. Dale of the Department of Aeronautical and Astronautical Engineering at The Ohio State University conducted these tests. The markers successfully withstood these tests, with the marker boards both horizontal and tilted thirty degrees.

The final merker design is shown in Fig. 7. The markers were erected so that at least 1.5 m of the conduit is above the snow surface.

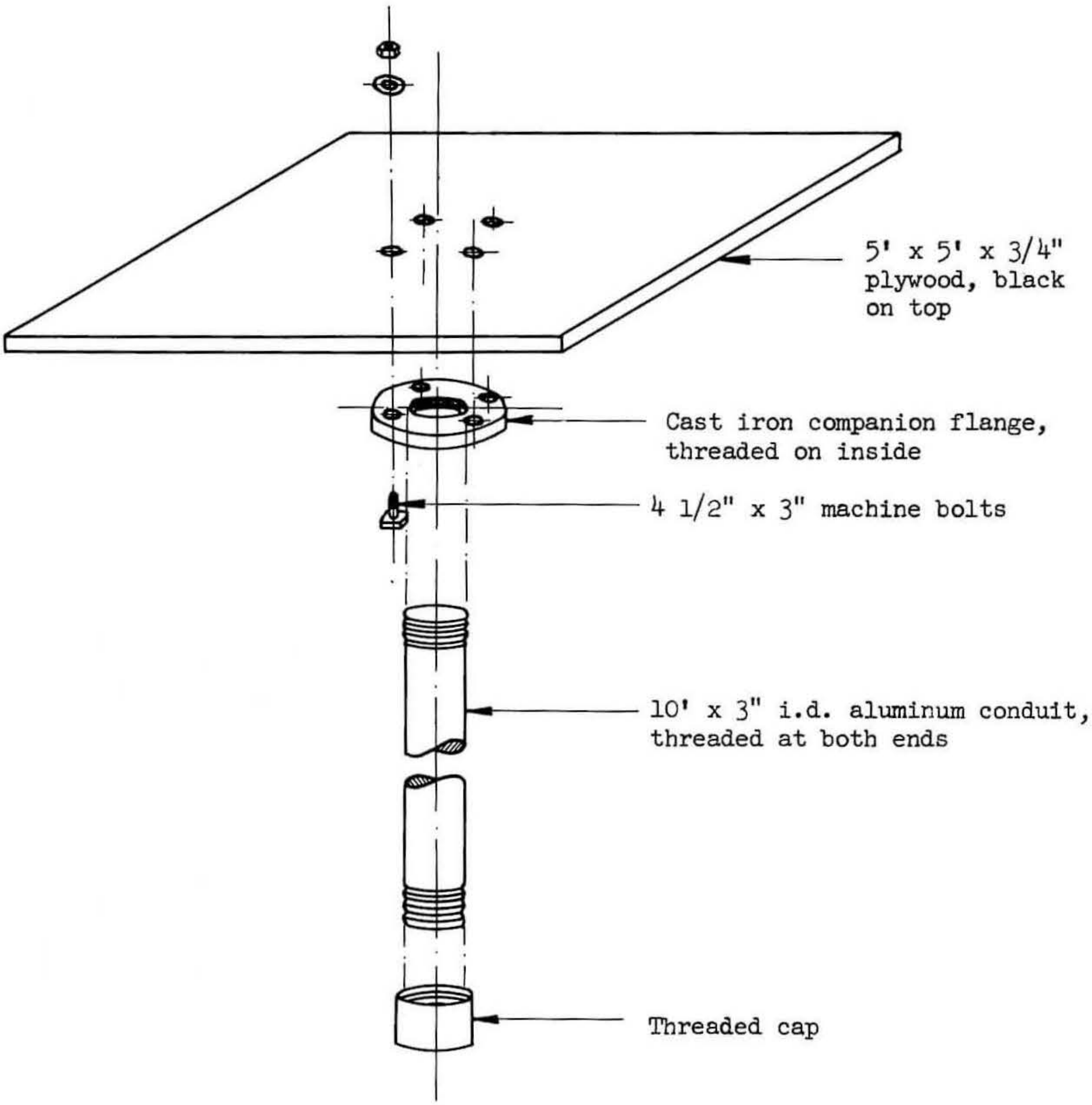


Figure 7 Photographic Marker

Thus, assuming an average snow accumulation of thirty centimeters per year, the boards will remain above the snow for five years.

A sample marker was constructed of available material and erected at Byrd Station in the winter of 1962. The marker weathered several storms and was still in good condition in February, 1963, with no snow on top. Unfortunately, the surface of the sample marker was not painted so no evaluation of paint weathering was possible.

No information was available on the best kind of paint to use on the plywood surface. Since it was necessary to paint the markers in a very short time to meet a shipping deadline, two coats of black quick-drying shellac-base paint were applied. It is hoped that this is sufficient to assure long-term visibility under Antarctic conditions.

The black surface, of course, is primarily intended for contrast on the photography. Black will also help to melt fallen snow from the top of the marker. The melting action was observed by the field party on the return trip from Mt. Chapman. Five centimeters of snow had fallen during a calm period. The sun came out and melted all snow from the marker tops in a few hours. The melted snow formed icicles at the edges of the boards.

With a little practice, a marker could be assembled in the field in less than five minutes. Damaged threads to the aluminum conduit caused some difficulty. Also, during shipping, some of the conduits had been slightly flattened at one end. The cap over one end of the conduit ensured at least one good threaded end.

The weight of an assembled marker was nearly ninety pounds. The total marker weight transported was over 8 tons for the 180 markers. If this method of ice movement study is expanded, adequate markers of less weight would simplify the logistics problems.

2. Surveying Equipment

The only surveying equipment required was a winterized Wild T2 theodolite with tripod, two barometric altimeters, two stop watches, a WWV communications receiver, and a 100 meter steel tape. A subtense bar was taken but was used only to calibrate the steel tape. The U. S. Hydrographic Office Publication 314 and the American Nautical Almanac were used for computing navigational fixes. A bicycle-wheel odometer was necessary for approximate distance and dead-reckoning position determination, since the Nodwell vehicles were not equipped with odometers. Flagged bamboo stakes were used as surveying signals.

C. INITIAL HEADING

Several observations were made from a point at Byrd Station to determine geographic position. From this, the plotted position of Mt. Chapman was used to compute the initial heading from Byrd Station. Solar azimuth observations were made, and the base point markers (Fig. 8) of Array Zero were set up along the initial heading, about one kilometer southeast of the fuel tunnel hatch. The initial navigational heading was determined with an estimated standard error of plus or minus two minutes of arc. This accuracy was more than sufficient for navigation, since the plotted position of Mt. Chapman was of doubtful accuracy.

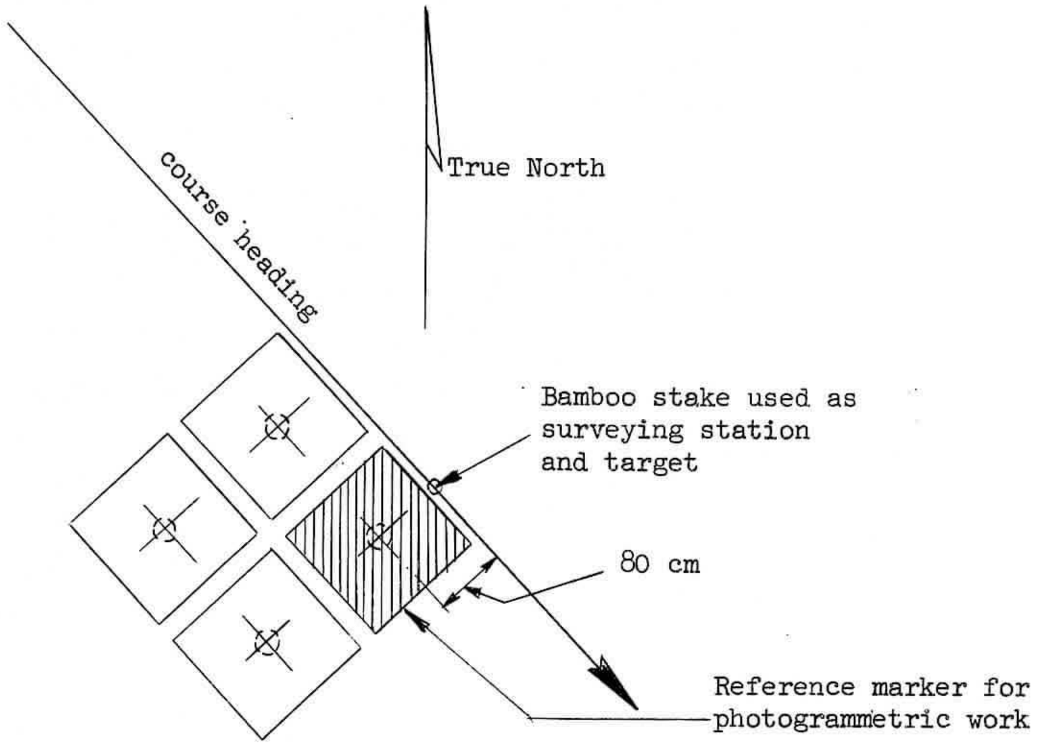


Figure 8. Base Point Marker Placement

D. MARKER PLACEMENT BETWEEN ARRAYS

Between the control arrays, markers were placed three to seven kilometers apart. Double markers and four marker squares (as in Fig. 8) were used about every fourth location (see Table I). These multiple markers were used to give the aerial photographer a visual check on his course. The correct heading in the field was maintained as follows:

1) The two vehicles traveled in line about three or four kilometers apart.

2) The rear party, at the last established marker, sighted back with the theodolite to the preceding marker and turned exactly 180°.

3) The forward party, after traveling the prescribed distance from the last established marker, stopped and made radio contact with the rear party.

4) Following radio instructions, the forward party moved a flagged bamboo stake left or right to the correct heading for the next marker. When the flagged stake coincided with the cross-hair in the theodolite, the rear party ordered the stake fixed. The correct marker position thus was established.

5) The forward party then measured eighty centimeters to the right (southwest) of the stake and bored the marker hole with a SIPRE ice auger. (All markers were offset in this way to allow easier re-observation when necessary.)

6) The marker was assembled and placed on its side with the black surface facing forward (southeast).

7) The forward party then drove ahead, keeping the black square of the reclining marker in line with the rear vehicle three to seven kilometers behind. In this way the forward vehicle stayed near the correct heading. In good weather, the forward party kept on course by looking back at the tracks of their vehicle, and steering to keep the tracks in a straight line.

8) Meanwhile, the rear party releveled the theodolite and measured the clockwise angle from the marker behind to the marker ahead (Fig. 5). At least one set of direct and reverse observations was made. When necessary, another set was taken to obtain a standard error of plus of minus two seconds in determining the angle. All observations were made

from and to the bamboo stake locations, rather than the photo markers. Since each marker was offset the same distance and direction from its signal flag, the measured angles apply to the markers as well as to the signal flags.

9) The rear party then set the marker in its hole, measured the height of the board above the snow surface, and proceeded to the next marker.

Barometric altimeters were read by both parties at each marker location. Readings were also taken on the return trip. The altimetry from the return trip was corrected for temperature and wind (Chapman, 1960) and is listed in Table I, and charted in Fig. 9. Return trip altimetry was used because of the much shorter elapsed time between readings at the marker locations.

The profile of the Horlick Mountains traverse, 1958-1959, is also shown in Fig. 9. The traverse traveled slightly southwest of the marker line, but at Mt. Chapman the group veered east, and passed over the site of Array Six. The difference between the two height determinations of Array Six from Byrd Station is only one meter. This is not a realistic accuracy indicator for barometric altimetry. The standard error of barometric height determination at Array Six in this study is estimated at plus or minus ten meters.

In some instances, surface relief limited visibility to less than the desired marker spacing. When this occured, an auxiliary flag was placed between the marker locations to maintain the traverse azimuth. The average time required per marker was 54 minutes, including travel time between markers at 6 to 9 km per hour. Mean separation between markers is 4.2 km, minimum separation is 3.0 km and maximum separation is 10.6 km.

··········· Heights Determined on Return Trip. Listed in Table I.

——— Heights from Horlick Mts. Traverse, 1958 - 1959, Over Approximately the Same Route, Adjusted to Fit Only Distance.

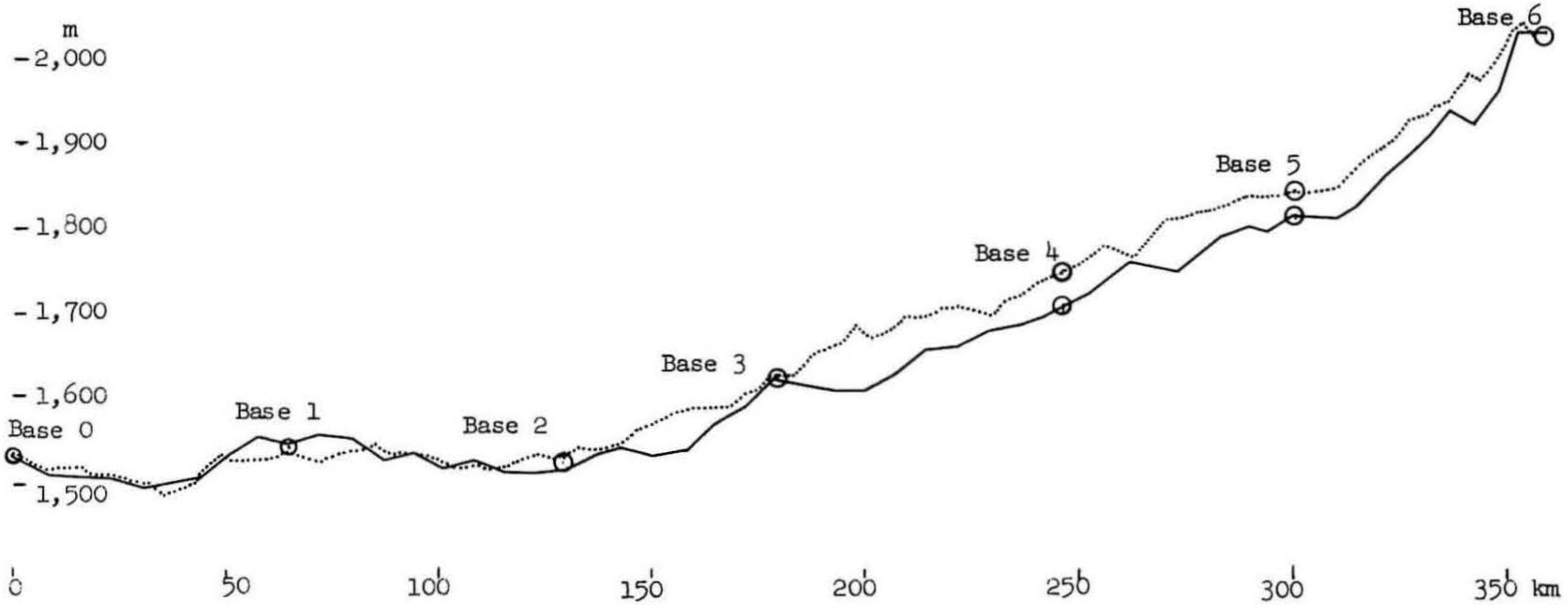


Figure 9. Height Profile by Barometric Altimetry
Byrd Station to Mt. Chapman

E. CONTROL ARRAYS

1. General

Each array usually consists of fourteen markers placed as in Fig. 6. The base point of each array (point 5 in the enlargement in Fig. 6) was the originating point for all array surveying. The markers A, B, C, and D were placed by traveling at approximately right angles to the course heading. Markers E, F, G, and H were placed by traveling from B or D at approximate right angles to the ABCD marker line, or roughly parallel to the heading.

The distances between the markers were made as long as possible to give added strength to the base, azimuth, and slope determinations in the aerial triangulations. Photographs from 6,000 m above the surface cover 4.5 km on each side of the course heading. To allow for possible course deviations of the photographic aircraft, the side markers were placed only 3.4 km on each side of the course heading. In several cases, intervisibility problems did not permit the optimum location of the markers.

Four markers were erected at the base point (Fig. 8). From above, these markers form a black square three meters on a side. This serves as a visual navigation aid to the aerial photographer and presents an unmistakable photographic image of the base point. The referpnce marker for the base point is shaded in Fig. 8.

The marker placement was designed to serve the following functions:

a) Relative Heights

The relative heights of points A, B, C, D, E, F, G, and H are determined. From these, the slopes are obtained for use in the slope adjustment of the triangulated strip model. The points are located nearly parallel with what will be the x and y directions in the strip coordinate system.

b) Base Line

The principal base line is BD. Lines EF and GH serve as secondary base lines when the intersected marker positions are sufficiently well determined. Lines AD and BC are emergency bases, for use if one side of the outside markers should not appear on the photograph. All base lines run nearly perpendicularly to the long axis of the strip. This is desirable for several reasons, one of which is the increased photogrammetric accuracy when both ends of the base line are in the same model.

c) Azimuth

All of the above base lines may be used for azimuth control of the adjustment.

2. Array Six

The control array at the end of the strip near Mt. Chapman was different from the other arrays. Ground control points on the mountain provide the control information. Array Six was erected about four kilometers from the mountain to provide an additional base and azimuth, and several additional height values. These will be used with the mountain points in adjusting the initial aerial triangulation. A sketch map of the mountain is shown in Fig. 10 with the locations of the intersected mountain control points. Notice the comparatively short base line determined by the mountain points A_1 and M_2. Note also the small area delimited by the vertical control points A_2, B_1, C_1, E_1, F_1, G_1, and M_1.

Using only the mountain control points, the correct absolute orientation of the last model in space can be determined. However, for more accurate orientation the longest possible base line and a larger area delimited by the vertical control points is desired. By using the markers in Array Six, a more accurate orientation can be made with the initial photography. After the orientation, the x,y,H coordinate values of any number of new mountain control points can be determined with the stereo instrument. (Possible locations for these new mountain control points are shown in Fig. 10.) In this way future photographs can be oriented with high accuracy, using only the old and new mountain control points.

3. Surveying Procedure

The most successful approach in surveying the control arrays was to survey and erect markers at the same time. The procedure was as follows:

a) Flagged stakes were placed at "Stake", the base point, and at a point ahead of the base point on the course heading (point 5-1 in Fig. 6).

b) Flagged stakes then were placed at points A, B, E, and G. Markers were erected at E and G at the same time that the stakes were placed. All of the markers were placed eighty centimeters southeast of their respective signal flags. Horizontal angles were always measured from the signal flag sites to other flags. Thus, the marker network was identical to the surveyed flag network, but moved eighty centimeters southeast.

c) After the flags and markers were placed at points E and G, vertical and horizontal angles were measured at points B and A and these markers were offset and erected.

d) The procedure was repeated for the other side of the array.

e) Angles were measured from "Stake", the base point, and one of the two points ahead of, or behind, the base point on the course heading (4-8 or 5-1 in Fig. 6).

f) The base line was taped from the base point to Stake, a distance of about five hundred meters, and the four base point markers set up.

g) After all survey work was completed, the flag at Stake was taken down. All other flags were left in place by their respective markers.

The above procedure was followed at Array Three and at subsequent arrays. In preceding arrays, no surveying was done until all flags were placed. After the surveying was completed, all markers were erected and all flags removed. This procedure took more time than the method initially used at Array Three.

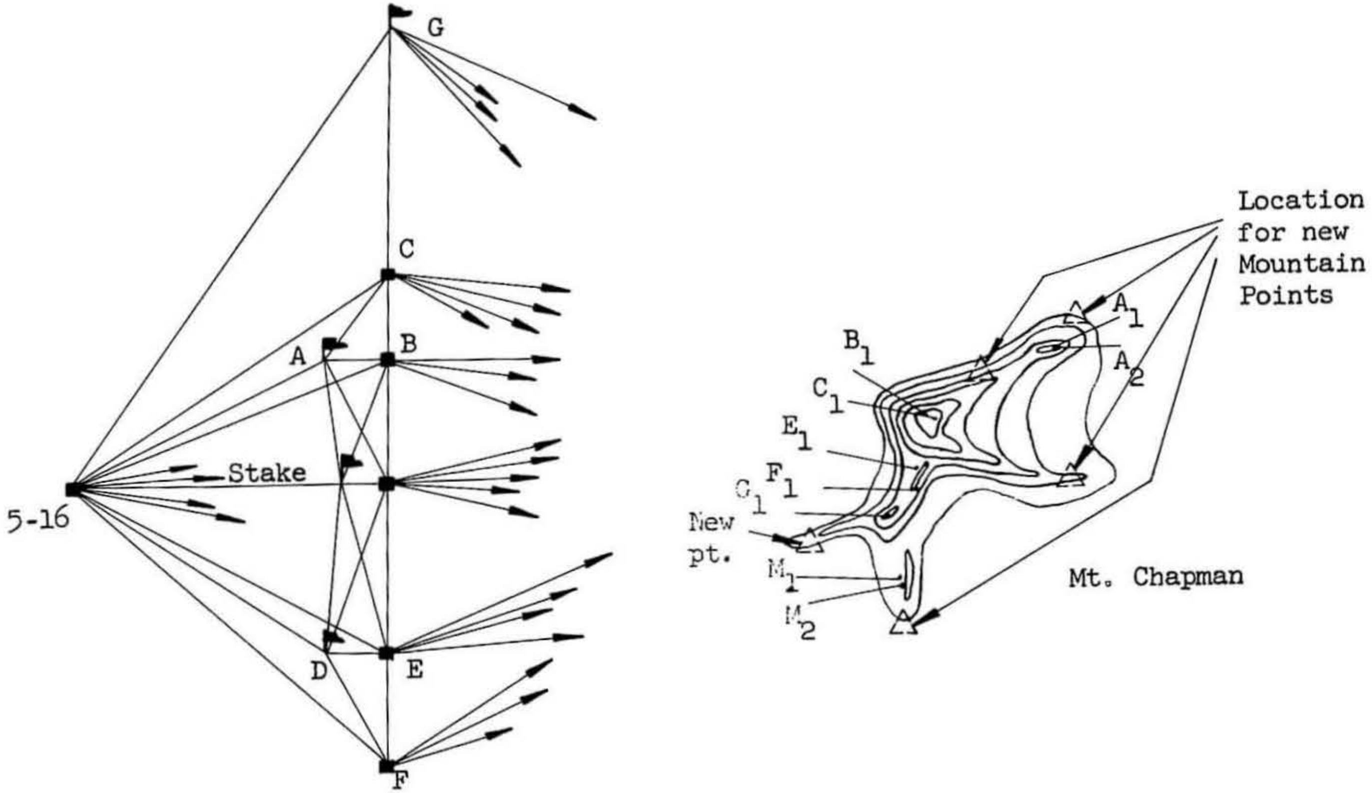


Figure 10. Sketch Map of Mt. Chapman and Array Six, Showing Mountain Control Points

The horizontal positions of all markers in the array were computed from the measured base line and angles. A plane rectangular coordinate system was established in each array, with the line from Stake to the base point (or vice versa) as the plus X axis. Coordinates of all markers were thus obtained. This individual coordinate system merely serves to compute distances and angles within the array, and is not connected to the coordinate systems of other arrays.

Heights of all markers were measured by reciprocal or non-reciprocal vertical angles, and were referred to a value of zero at the base point of each array.

4. Angle Measurements

Vertical and horizontal directions were normally observed as follows, using Array Five as an illustration:

At point A to Points 5, Stake, 4-8, G, B, E, and 5-1;
at point B to points A, 5, Stake, 4-8, G, E, and 5-1;
at point C to points 5, 5-1, F, D, H, 4-8, and Stake;
at point D to points C, 5, 5-1, F, H, 4-8, and Stake;
at Stake to points B, A, 5, C, and D;
at base point 5 to every observable point;
at point 5-1 to every observable point but Stake.

Horizontal angles were measured to a standard error of plus or minus two or three seconds of arc, and vertical angles to plus or minus five seconds of arc. A slight amount of trouble was encountered with signal stakes that were not vertical.

The final desired standard position error of the array markers was $\pm$ 0.4 m. A formal adjustment procedure was unnecessary to achieve this standard error, except for Array One, where one side of the array was rigorously adjusted to obtain the desired positional standard error values. Standard error of each marker coordinate is listed in Table III.

5. Base Line Measurement

The bases were measured on the snow surface with an inexpensive 100 meter steel tape, using 20 pounds tension. In tapes of this sort, the temperature expansion corrections are not too reliable. To compensate for this, all base measurements were made at, or close to, $0^{\circ}F$. The first base, that of Array Zero, was measured separately by subtense bar. This subtense value was used as a true value for the base, and the taped base (taped at $4^{\circ}F$) was corrected to match it. The tape correction for $4^{\circ}F$ was then determined to be -0.049 m/100 m, which agreed reasonably well with the value of -0.041 m/100 m, scaled from the small temperature correction ruler supplied with the tape. The correction determined from the subtense bar measurement was applied to the taped bases of all arrays. Where the temperature differed from $4^{\circ}F$, the tape correction was adjusted at the rate of 0.00062 m/100 m/$^{\circ}F$, the rate of change given by the tape correction ruler.

The base was measured from the base point to Stake, and then back to the base point. The two values were averaged and corrected for temperature. Reduction to sea level and slope corrections also were applied. Considering the snow undulations, the bow of the tape, incorrect tape temperature data, tension errors, etc., the final accuracy of each taped base is estimated at plus or minus one or two centimeters standard error which is quite sufficient.

6. Azimuth Measurement

The azimuth was carried forward between base arrays. The clockwise horizontal angle between the rear and forward markers was measured at each point between the arrays (see III, D of this report). The difference between each angle and 180° (Table I) were summed for all angles between two arrays (Table II). Thus, for each array, the azimuth of a line from the base point to the preceding marker refers to a common reference, the course heading. This reference line was given an arbitrary value of 90°. In Table II, the angle is listed between the preceding marker and the X axis of the array as observed from each base point.

The approximate standard error in determining a single angle between markers is plus or minus two seconds of arc. From 15 to 21 angles were observed between each array (Table I). The azimuth between arrays thus is known within a standard error of plus or minus eight or nine seconds of arc. This standard error is well within the necessary standard error of thirty seconds and the desired value of fifteen seconds. The knowledge of absolute azimuth is limited to the determination of the initial heading, in this case plus or minus two minutes. However, only a rough knowledge of absolute azimuth is needed to refer the surface displacement vectors to true directions.

The above method of maintaining azimuth is recommended for future field work in this study. It is possible to use geographic azimuths obtained from solar observations at each array. However, the use of solar azimuths in these latitudes is not recommended for the following reasons:

a) Solar azimuth observations require either a detailed knowledge of atmospheric refraction, or a precise radio time signal, or both, to obtain results which are only about half as accurate as those of the recommended method.

b) More precise position determination is necessary to reduce geographic azimuths in the strip coordinate system.

c) Solar observations will require at least as much time as the six working days of the recommended method.

d) More computation time is needed.

e) A higher degree of skill is required.

f) Much more time is required to check the observations for gross errors. The recommended method is checked by making two angle measurements at each point.

IV. AERIAL PHOTOGRAPHY

A. CAMERA AND FILM

A T-11 camera was used for the initial aerial photography. This camera has a metrogon objective with high radial distortion. Maximum radial distortion errors are $\pm$ 0.1 mm. With the aid of a distortion correction plate in the stereo instrument, the effect of these distortions can be largely removed during the aerial triangulation. It must be noted, however, that the distortion has been determined to only $\pm$ 0.02 mm probable error. Precision aerial cameras are available with radial distortion of less than $\pm$ 0.01 mm and with superior resolution. The use of such cameras in future surface movement work would mean a decrease in the necessary ground control and number of models, and an increase in accuracy for the aerial triangulation. In any photogrammetric work, it should be obvious that the camera is the most important piece of equipment. Precision high performance aerial cameras with low distortion objectives are very strongly recommended for any future ice movement work.

Cellulose acetate butyrate film was used for the initial photography. Acetate film is adequate for many uses, but for the accuracy required in this work, Kodak Estar or Du Pont Cronar films are recommended. These new polyestar films possess dimensional stability superior to that of acetate film.

B. PHOTOGRAPHIC FLIGHTS AND QUALITY

Photography was taken by Navy Special Air Development Squadron Six in early February, 1963. Four strips were photographed of the entire line of markers, from 3,000 m and 6,000 m above the surface, and with 60 to 80 percent overlap. Normally, only the 6,000 m, 60 persent overlap photography would be necessary. The photography from 3,000 m will be used where the snow surface does not give enough texture in the photographs to make stereoscopic observations. Such a lack of texture might be caused by clouds or haze, sun altitude, incorrect camera aperture, or faulty developing. The photography with 80 percent overlap ensures sufficient overlap, and may give two strips of 60 percent overlap photographs by using every other photograph.

The next task is to scan the photographic negatives and paper prints of the photography to select the exposures to be used in the aerial triangulation. At this time, the quality of the photographic flight will be determined. As there are several strips of photographs, it should not be difficult to select exposures that will permit aerial triangulation of the highest possible accuracy (considering the camera and film that were used).

V. FUTURE WORK

A. FIELD WORK

When future aerial photography is taken, a minimum of field work must be performed. Azimuths must be measured for all arrays, using the method recommended in III, E, 6 of this report. Relative heights of array markers may have to be remeasured. Change of base line lengths has been estimated (Bull, 1963) to be unlikely to exceed one percent of the surface movement over a five-year period. Thus, it may not be necessary to remeasure a 600-meter base line and survey the array by horizontal angles. In any case, two men, equipped with motor toboggans, will be able to perform all necessary survey work.

In the course of the field work, glaciological measurements will also be made. This will be a continuation of studies begun during the initial field work (Koerner, 1963).

Full drums of gasoline were cached at Arrays Two through Six for future field work.

B. PHOTOGRAPHY

Future aerial photography may be flown at any time shortly before, during, or after the field work, as long as the black marker tops are not snow covered or faded.

The 1963 photography will show the quality of photography to expect in the future. Adjustments in overlap and flying height can be made so that fewer strips will be required for future flights.

C. AERIAL TRIANGULATION AND ICE MOVEMENT DETERMINATION

Future photography will be triangulated in the same manner as the original photographs. Elevations on Mt. Chapman will give a fixed height reference. The fixed Mt. Chapman base lines will furnish scale and azimuth values and allow the re-establishment of the original strip coordinate system. The new field control information on azimuths, etc., will be used for the strip adjustment.

The adjusted strip coordinates of the markers then can be directly compared with the adjusted coordinates of February, 1963. This comparison will give both the magnitude and the direction of the surface movement for each of the 134 marker positions.

VI. MATERIAL TO BE INCLUDED IN NEXT REPORT

When the best exposures of the 1963 photographs are selected, glass or plastic diapositives will be made. At least two triangulations will be performed, one from each end of the strip. The double determination will indicate triangulation accuracy and strengthen the coordinate determinations.

The next report will cover the following items:

1) Evaluation of photographic image quality,
2) Critique of photographic tilt, overlap, crab, and flight deviations,
3) Field work errors or discrepancies,
4) Triangulation of the strip and adjustments,
5) Coordinates of the markers, and
6) Selection of additional mountain control points.

VII. CONCLUSIONS

Based on the initial field work, there is every assurance that this first ice movement study can be successful. If a more precise aerial camera can be used for future work, results will be more accurate, less expensive, and more quickly available.

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TABLE I MARKER PLACEMENT DATA

EXPLANATION OF TABLE COLUMNS

Marker

Photographic markers are numbered from preceding array. Auxiliary signal flags used to maintain azimuth have lower case suffixes. The number in parenthesis indicates the number of markers, at multiple marker points.

Distance

Cumulative distance in kilometers is given from base point at Array Zero.

Height

Height above sea level is given in meters, as determined by barometric altimetry. Reference value is 1529 m at Byrd Station. Heights apply to undisturbed snow surface at each marker. (See also Fig. 8.)

Marker Height

Height in meters from undisturbed snow surface vertically to top of iron flange.

Displacement

Marker displacement in meters is positive to southwest (+) and negative to northeast (-) of the course line and is calculated from angle measured at each marker and distance between markers. (See also Fig. 5.)

Azimuth

The azimuth is determined as:

Azimuth angle minus 180°. (See Fig. 5.)

TABLE I

Marker	Distance km	Height m	Marker Height m	Displacement m	Azimuth
0 (4)	0.00	1530	1.68	0.00	00"
0-1	3.31	1523	1.75	0.00	10"
0-2	6.74	1510	1.55	0.18	04"
0-3	9.87	1517	1.60	0.39	- 12"
0-4	12.94	1519	1.52	0.42	- 16"
0-5	16.27	1517	1.52	0.19	14"
0-6	19.59	1504	1.57	0.19	00"
0-6a	21.50			0.19	02"
0-7	22.59	1505	1.60	0.21	- 02"
0-8	25.80	1500	1.63	0.21	03"
0-9 (4)	29.02	1497	1.73	0.26	01"
0-10	32.30	1494	1.78	0.32	- 08"
0-11	35.52	1486	1.73	0.26	- 12"
0-12	38.59	1490	1.65	0.02	20"
0-13 (2)	41.75	1497	1.98	0.00	04"
0-14	44.80	1522	1.75	0.19	04"
0-15	47.88	1530	1.70	0.37	- 08"
0-16	50.95	1527	1.80	0.43	- 01"
0-16a	54.33			0.48	00"
0-16b	57.73	1512		0.53	00"
0-16c	58.52	1535		0.55	- 04"
0-16d	60.03	1537		0.55	- 02"
1 (4)	61.52	1531		0.53	- 04"
1-1	65.32	1539	1.75	0.42	- 04"
1-2	69.17	1531	1.70	0.21	- 02"
1-3	72.97	1528	1.60	- 0.03	32"
1-4	76.73	1534	1.75	0.32	1'10"
1-5 (2)	80.55	1538	1.60	1.96	2'13"
1-6	84.47	1545	1.70	1.13	28"
1-7	88.37	1535	1.70	1.43	34"
1-8	92.26	1536	1.70	1.75	04"
1-9 (4)	96.00	1533	1.83	2.17	27"
1-10	99.94	1526	1.75	3.11	- 04"
1-11	103.84	1520	1.73	3.96	- 55"
1-12	107.66	1522	1.80	3.77	- 03"
1-13 (2)	111.45	1513	1.57	3.52	38"
1-14	115.62	1519	1.80	4.02	- 10"
1-15	119.06	1528	1.83	4.28	- 04"
1-16	122.89	1533	1.63	4.49	- 03"

TABLE I
continued

Marker	Distance km	Height m	Marker Height m	Displacement m	Azimuth
2 (4)	128.55	1530	1.75	4.70	10"
2-1	133.19	1543	1.70	5.10	- 29"
2-2	138.02	1539	1.78	4.84	12"
2-3	142.93	1548	1.78	4.81	12"
2-3a	145.60			4.72	- 19"
2-4	147.29	1564	1.83	5.04	- 18"
2-4a	149.36			4.97	- 21"
2-5 (2)	152.77	1579	1.73	4.51	36"
2-5a	154.92			4.59	08"
2-6	156.41	1584	1.73	4.70	- 22"
2-7	160.19	1587	1.78	4.59	- 2'06"
2-8	164.17	1589	1.70	2.04	- 4'03"
2-9	168.34	1591	1.65	4.28	- 1'42"
2-9a	169.77			4.34	48"
2-10	171.89	1609	1.57	4.92	11"
2-10a	173.87			5.57	01"
2-11	176.38	1606	1.90	6.65	- 02"
3 (4)	179.62	1623	1.57	7.08	- 41"
3-0a	180.94			7.24	02"
3-1	183.42	1625	1.98	7.58	1'22"
3-1a	185.75			8.82	07"
3-2	187.31	1649	1.80	9.70	- 57"
3-3	190.39	1657	1.78	10.61	09"
3-4	194.89	1666	1.68	12.12	- 01"
3-5	198.58	1684	1.75	13.33	00"
3-5a	199.88			13.79	- 09"
3-6	202.36	1671	1.75	14.50	03"
3-7	206.58	1681	1.78	15.77	- 08"
3-8	209.89	1698	1.75	16.64	18"
3-9 (4)	214.09	1696	1.75	18.11	07"
3-10	217.82	1707	1.78	19.54	18"
3-11	221.99	1708	1.83	21.50	- 10"
3-12	225.65	1702	1.90	23.05	- 17"
3-13	229.16	1699	1.78	24.24	09"
3-14	233.24	1715	1.83	25.80	20"
3-15	236.82	1723	1.98	27.51	- 34"
3-16	240.26	1734	1.83	28.58	05"

TABLE I
continued

Marker	Distance km	Height m	Marker Height m	Displacement m	Azimuth
4 (4)	243.61	1741	1.80	29.73	28"
4-0a	245.91			30.82	25"
4-0b	248.03			31.58	15"
4-1	250.14	1758	2.06	32.48	21"
4-1a	252.17			33.56	- 01"
4-1b	254.74			34.91	- 01"
4-2	256.71	1783	1.78	35.92	- 16"
4-2a	259.68			37.24	- 02"
4-3 (2)	263.24	1769	1.78	38.77	- 02"
4-3a	265.98			39.93	- 19"
4-3b	269.07			40.94	- 09"
4-4	269.84	1810	1.68	41.17	- 2'19"
4-5	276.40	1819	1.68	38.63	- 3'04"
4-5a	279.59			34.56	11"
4-5b	282.23			31.32	06"
4-6 (2)	282.92	1825	1.98	30.50	- 2'41"
4-6a	286.29			23.85	- 08"
4-7	289.89	1840	1.78	16.58	- 2'58"
4-7a	293.56			6.02	- 2'01"
4-8	296.86	1841	1.75	- 1.54	- 2'19"
5 (4)	301.06	1844	1.65	- 14.00	- 52"
5-1	304.38	1842	1.78	- 24.67	- 1'08"
5-2	307.71	1848	1.73	- 36.49	- 1'14"
5-3	311.01	1851	1.80	- 49.38	- 1'25"
5-3a	313.73			- 61.13	- 51"
5-4	314.31	1869	1.83	- 63.77	- 1'04"
5-5 (2)	317.67	1882	1.78	- 80.17	- 1'22"
5-6	320.87	1897	1.70	- 97.07	- 1'00"
5-7	324.16	1907	1.85	-115.34	- 1'13"
5-7a	326.62			-129.92	- 56"
5-8	327.57	1926	1.75	-135.79	- 1'00"
5-9 (4)	330.88	1935	1.85	-157.28	- 1'14"
5-10	334.24	1949	1.83	-180.30	- 1'38"
5-11	337.61	1955	1.70	-204.90	- 1'42"
5-12	340.94	1985	1.65	-230.93	- 1'25"
5-13 (2)	344.35	1979	1.60	-258.98	- 1'19"
5-13a	345.99			-273.12	- 1'50"
5-14	347.64	1995	1.83	-288.12	- 1'47"

TABLE I
continued

Marker	Distance km	Height m	Marker Height m	Displacement m	Azimuth
5-15	350.92	2032	1.88	-319.82	- 2'04"
5-15a	352.38			-334.86	08"
5-16	354.17	2045	1.78	-353.11	- 04"
5-16a	356.05			-372.39	- 05"
6 (4)	357.53	2030	1.52	-396.72	

TABLE II

ROTATIONS TO BRING ARRAY AZIMUTHS

TO COMMON REFERENCE

Array	Sum of survey angle differences between arrays (Table I) up to base point	Angle between rear marker and X-axis of array, measured at base point	Rotation correction for azimuth in each array
0	- 0'03"	- 4'44"	4'44"
1	- 0'03"	- 28'41"	28'44"
2	0'08"	13'35"	- 13'43"
3	1'07"	22'45"	- 23'52"
4	1'10"	1^{o}12'40"	-1^{o}13'50"
5	- 10'12"	- 1'44"	- 11'56"
6	- 35'17"	1^{o}00'29"	- 25'12"

TABLE III

ARRAY MARKER COORDINATES

Point	X, meters		Y, meters		Relative surface height, ΔH meters		Height of marker board above snow, meters	Comments
	X	standard error(±)	Y	standard error(±)	ΔH	standard error(±)		
ARRAY ZERO								
Base point	456.88	0.01	0.00	0.0	0.0	0.0	1.68	Add 4'44" to all azimuths obtained from these coordinates, to rotate the azimuths into a common reference system.
Stake	0.00	0.00	0.00	0.0				
A	459.1	0.1	1597.2	0.1	7.7	0.1	1.80	
B	460.9	0.1	3170.1	0.1	18.1	0.1	1.88	
C	455.0	0.1	-1661.5	0.1	2.2	0.1	1.55	
D	454.9	0.1	-2217.2	0.1	- 0.1	0.2	1.65	
E	6.1	0.1	2021.4	0.1	12.9		1.65	
F							1.60	
G	3802.2	0.2	3542.5	0.2	6.5	0.3	1.78	
H	3793.1	0.2	-3179.0	0.2	- 13.6		1.42	
O-1	3797.5	0.3	- 4.5	0.3	- 9.0	0.5	1.75	

TABLE III
continued

Point	X, meters		Y, meters		Relative surface height, ΔH meters		Height of marker board above snow, meters	Comments
	X	standard error(±)	Y	standard error(±)	ΔH	standard error(±)		
<u>ARRAY ONE</u>								
Base Point	473.2	0.01	- 0.81	0.02	0.0	0.0	1.75	Add 28'44" to all azumiths obtained from these coordinates, to rotate the azimuths into a common reference system.
Stake	0.0	0.0	0.0	0.0				
A	496.8	0.1	1649.2	0.1	2.3	0.2	1.75	
B	507.7	0.1	2543.9	0.1	0.8	0.5	1.73	
C	461.3	0.2	-1594.1	0.2	- 2.8	0.2	1.75	
D	466.0	0.2	-3608.2	0.2	- 8.1	0.4	2.03	
E	-2605.8	0.1	2765.2	0.1	9.0	0.4	1.75	
F	-2590.6	0.1	-3378.1	0.2	- 11.9	0.5	1.75	
G	3552.2	0.4	2685.4	0.4	2.0	0.2	1.57	
H					- 16.0	1.0	1.68	

TABLE III
continued

Point	X, meters		Y, meters		Relative surface height, ΔH meters		Height of marker board above snow, meters	Comments
	X	standard error(±)	Y	standard error(±)	ΔH	standard error(±)		
ARRAY TWO								
Base point	0.0	0.0	0.81	0.02	0.0	0.0	1.75	Subtract 13'43" from all azimuths obtained from these coordinates to rotate the azimuths into a common reference system.
Stake	429.7	0.01	0.0	0.0				
A	- 10.7	0.2	1671.1	0.2	12.2	0.2	1.83	
B	- 17.9	0.2	2759.0	0.4	17.7	0.2	1.83	
C	6.9	0.2	-1552.3	0.2	- 3.1	0.3	1.68	
D	14.2	0.2	-3475.6	0.4	- 9.6	0.3	1.85	
E	-3475.8	0.3	2734.3	0.4	3.4	0.3	1.80	
F	-2673.3	0.2	-3481.9	0.2	- 6.6	0.3	1.75	
G	894.0	0.3	2765.6	0.4	21.8	0.1	1.63	
H	3182.2	0.5	-3486.3	0.5	3.1		1.70	

TABLE III
continued

Point	X, meters		Y, meters		Relative surface height, ΔH meters		Height of marker board above snow, meters	Comments
	X	standard error(±)	Y	standard error (±)	ΔH	standard error(±)		
<u>ARRAY THREE</u>								
Base point	0.0	0.0	0.0	0.0	0.0	0.0	1.57	Subtract 23'52" from all azimuths obtained from these coordinates to rotate the azimuths into a common reference system.
Stake	446.06	0.01	0.0	0.0				
A	- 9.8	0.2	1676.0	0.2	- 7.0	0.2	1.42	
B	297.2	0.2	4369.3	0.2	8.7	0.4	1.69	
C	16.3	0.2	-1679.2	0.2	- 1.3	0.5	1.69	
D	20.8	0.2	-2561.3	0.2	- 4.7	0.2	1.80	
E	-4791.9	0.2	4298.9	0.2	- 17.8	0.2	2.11	
F	-3719.3	0.3	-2583.0	0.3	- 15.0	0.5	1.85	
G	3870.3	0.2	4562.4	0.2	29.7	0.3	1.73	
H	3822.7	0.3	-2520.7	0.3	- 4.2	0.3	1.73	
2-11					- 12.7	0.4	1.91	

TABLE III
continued

Point	X, meters		Y, meters		Relative surface height, ΔH meters		Height of marker board above snow, meters	Comments
	X	standard error(±)	Y	standard error(±)	ΔH	standard error(±)		
<u>ARRAY FOUR</u>								
Base point	667.83	0.01	0.0	0.0	0.0	0.0	1.80	Subtract $1^{\circ}13'50''$ from all azimuths obtained from these coordinates, to rotate the azimuths into a common reference system.
Stake	0.0	0.0	0.0	0.0				
A	627.6	0.2	1582.4	0.2	7.7	0.3	1.75	
B	579.5	0.2	3467.3	0.2	21.4	0.3	1.60	
C	755.9	0.2	-2123.1	0.2	- 10.9	0.2	1.80	
D	820.3	0.2	-3587.9	0.2	- 15.8	0.2	1.78	
E	-3202.5	0.2	3344.7	0.2	13.6	0.3	1.60	
F	-2774.5		-3886.3		- 27.6		1.83	
G	4450.7	1.0	3554.5	0.7	24.7	0.4	1.60	
H	4620.5		-3467.7		- 10.2	5.0	1.88	
3-16	-2687.0	0.2	- 70.9	0.2	- 6.2		1.83	

TABLE III
continued

Point	X, meters		Y, meters		Relative surface height, ΔH meters		Height of marker board above snow, meters	Comments
	X	standard error(±)	Y	standard error(±)	ΔH	standard error(±)		
ARRAY FIVE								
Base point	0.0	0.0	0.0	0.0	0.0	0.0	1.65	Subtract
Stake	586.99	0.01	0.0	0.0	0.0	0.0	0.0	11'56"
A	- 33.8	0.2	1729.7	0.2	6.4	0.1	1.78	from all
B	- 87.6	0.2	3430.0	0.4	10.7	0.1	1.83	azimuths
C	- 12.9	0.2	-1877.7	0.2	- 7.3	0.1	1.80	obtained
D	- 48.7	0.3	-3640.9	0.5	- 13.6	0.1	1.83	from these
E	-2627.9	0.4	-3074.4	0.4	6.8	0.2	1.83	coordinates,
F	-4090.8	0.4	-3549.1	0.4	- 9.1	0.3	1.83	to rotate
G	3584.8	0.3	3514.9	0.3	14.8	0.2	1.78	the azimuths
H	2859.6	0.4	-3739.3	0.4	- 12.2	0.4	1.78	into a
4-8	-3486.6	0.6	1.8	0.3	- 1.7	0.4	1.75	common
								reference
								system.

TABLE III
continued

Point	X, meters		Y, meters		Relative surface height, ΔH meters		Height of marker board above snow, meters	Comments
	X	standard error(±)	Y	standard error(±)	ΔH	standard error(±)		
ARRAY SIX								
Base point	524.45	0.01	0.0	0.0	0.0	0.0	1.52	Subtract 25'12" from all azimuths obtained from these coordinates, to rotate the azimuths into a common reference system.
Stake	0.0	0.0	0.0	0.0				
A	- 16.4	0.1	1324.1	0.1	19.5	0.1		
B	442.2	0.1	1280.1	0.1	27.8	0.1	1.91	
C	373.9	0.2	2200.0	0.2	30.0	0.1	1.93	
D	0.3	0.1	-1627.5	0.1	14.1	0.1		
E	542.5	0.1	-1770.3	0.1	15.8	0.1	1.93	
F	595.6	0.2	-2825.8	0.2	6.9	0.1	1.83	
G	650.6	0.4	4833.8	0.4	49.7	0.5		
5-16	-2809.4	0.2	- 58.7	0.2	13.9	0.1	1.74	
A_1	7629.2	0.4	1307.7	0.4	545.0	0.3		H & V control Pt.
A_2	7610.0	10.0	1250.0	10.0	577.2	0.8		
B_1	6180.0	10.0	620.0	10.0	703.7	0.6		
C_1	6286.0	3.0	583.0	1.0	709.4	0.8		
E_1	6320.0	10.0	10.0	10.0	207.4	0.3		Vertical control Pt.
E_2	6110.0	10.0	- 40.0	10.0	205.3	0.8		
F_1	6220.0	10.0	- 190.0	10.0	306.0	0.4		Vertical control Pt.
G_1	5752.2	0.2	- 445.5	0.4	399.8	0.7		Hor. control Pt.
L_1	7480.0	10.0	960.0	10.0	200.2	1.0		
M_1	5889.6	0.4	-1075.1	0.2	87.4	0.1		H & V control Pt.
M_2	5897.5	0.4	-1074.5	0.2	93.2	0.2		H & V control Pt.

Principal Investigator Robert B. Forest Date ________ 1963

Supervisor A. J. Brandenberger Date Sept. 1963

Executive Director Robert C. Stephenson AJ Date 9/25/ 1963